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Can massive Be/Oe stars be progenitors of long gamma ray bursts?

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ABSTRACT

Context. The identification of long-gamma-ray-bursts (LGRBs) is still uncertain, although the collapsar engine of fast-rotating massive stars is gaining a strong consensus.
Aims. We propose that low-metallicity Be and Oe stars, which are massive fast rotators, as potential LGRBs progenitors.
Methods. We checked this hypothesis by 1) testing the global specific angular momentum of Oe/Be stars in the ZAMS with the SMC metallicity, 2) comparing the ZAMS ($\Omega/\Omega_{\rm c}, M/M_{\odot}$) parameters of these stars with the area predicted theoretically for progenitors with metallicity $Z=0.002$, and 3) calculating the expected rate of LGRBs/year/galaxy and comparing them with the observed ones. To this end, we determined the ZAMS linear and angular rotational velocities for SMC Be and Oe stars using the observed $V\sin i$ parameters, corrected from the underestimation induced by the gravitational darkening effect.
Results. The angular velocities of SMC Oe/Be stars are on average $\langle\Omega/\Omega_{\rm c}\rangle=0.95$ in the ZAMS. These velocities are in the area theoretically predicted for the LGRBs progenitors. We estimated the yearly rate per galaxy of LGRBs and the number of LGRBs produced in the local Universe up to z=0.2. We have considered that the mass range of LGRB progenitors corresponds to stars hotter than spectral types B0-B1 and used individual beaming angles from 5 to 15°. We thus obtain $R^{\rm pred}_{\rm LGRB}\sim10^{-7}$ to $\sim10^{-6}$ LGRBs/year/galaxy, which represents on average 2 to 14 LGRB predicted events in the local Universe during the past 11 years. The predicted rates could widely surpass the observed ones [(0.2-3)$\times10^{-7}$ LGRBs/year/galaxy; 8 LGRBs observed in the local Universe during the last 11 years] if the stellar counts were made from the spectral type B1-B2, in accordance with the expected apparent spectral types of the appropriate massive fast rotators.
Conclusions. We conclude that the massive Be/Oe stars with SMC metallicity could be LGRBs progenitors. Nevertheless, other SMC O/B stars without emission lines, which have high enough specific angular momentum, can enhance the predicted $R_{\rm LGRB}$ rate.

Key words. Gamma rays: bursts – Stars: early-type – Stars: emission-line, Be – Stars: fundamental parameters – Galaxies: Magellanic Clouds

1. Introduction

Since their discovery, data on gamma ray bursts (GRBs) considerably increased, which today allow us to aim at preliminary statistical conclusions. The properties of GRBs and their possible connection to SN were reviewed by Woosley & Bloom (2006) and Fryer et al. (2007). Thus, there are at least 2 classes of GRBs according to the duration of the phenomenon: 1) short bursts that last less than 1 s and 2) long bursts, which are longer than 1-3 s hereafter LGRBs. Although the short GRBs might correspond to a violent merging of two compact objects, evidence is growing that suggests that the disruption of a massive star can be behind an LGRB (Fryer et al. 2007). A possible, but rare, third class of GRBs can be explained by a binary-star scenario (Tutukov & Fedorova 2007). However, proper identification of both the progenitor and the final nature of the phenomenon are still fairly uncertain. Nevertheless, a kind of consensus is gaining in the community that the collapsar engine during a supernova SNIb,c explosion, as proposed by Woosley (1993), might lead to allow the explanation of LGRBs. According to this hypothesis, the explosion follows a massive star collapse to a black hole. The circumstellar disk accretes onto the black hole and a bi-polar jet is formed (Hirschi et al. 2005). The infalling material must have enough angular momentum to remain in a disc before accretion.

New observational findings and the latest theoretical developments are steadily giving best founded constraints to understand the LGRBs phenomenon. The observations carried out by Iwamoto et al. (1998, 2000) support the idea that massive fast-rotating stars are at the origin of the LGRBs. Thöne et al. (2008) find that the LGRB

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GRB060505 is hosted in a low-metallicity galaxy, which is characterized by a high star-formation rate. The event seems to come from a young environment (6 Myrs) and from an object about 32 $M_{\odot}$. The latest models have tried to reproduce the evolution of stars until the end of their lives. In particular, for massive stars, they have been worked out until the GRBs phase. In the search for SNIb,c progenitors, WR stars with He-rich envelopes are recognized as possibly behind the GRBs events. In fact, Hammer et al. (2006) find that the LGRBs occur in areas of galaxies with WR stars.

Rotation has been recognized as a key point for understanding the appearance of GRBs (Woosley 1993; Hirschi et al. 2005; Yoon et al. 2006). Accordingly, to keep a large amount of angular momentum up to the last evolutionary phases before the collapse, GRBs progenitors should be massive objects with low initial metallicities and possibly display anisotropic winds (Meynet & Maeder 2007). Thus, from Yoon et al. (2006) it seems that WR stars with metallicities $Z \lesssim 0.002$ can be progenitors of GRBs. In the same sense, Modjaz et al. (2008) find that the SNIc-GRB association occurs when metallicities are lower than $0.6 \times Z_{\odot}$. Because stars with low metallicities can on average rotate faster, Hirschi et al. (2005) and Yoon et al. (2006) foresee that the number of GRBs must grow as the redshift increases, which seems to be confirmed observationally (Fryer et al. 2007). It might still be that the first massive stars, which were very metal-poor stars, were fast rotators. This is an additional reason for the frequency of GRBs being higher as the redshift increases. In this sense, Kewley et al. (2007) find a link between the location of cosmological LGRBs and the very low-metallicity galaxies.

Thanks to fast rotation and the concomitant efficient mixing of chemical elements, massive stars can undergo quasi-chemically homogeneous evolution to end up as helium WR stars satisfying the requirements for the collapsar scenario (Yoon et al. 2006; van Marle et al. 2008). Yoon et al. (2006) have calculated the quasi-chemically homogeneous evolution of magnetized massive stars. They produced diagrams of LGRBs progenitors as a function of their ZAMS rotational velocities and masses and of different initial metallicities. From these diagrams, it emerges that there must be an upper limit to the initial metallicity of LGRBs progenitors, which approximatively corresponds to that of the Small Magellanic Clouds (SMC). According to Maeder et al. (1999, and references therein), the SMC average metallicity is $Z \sim 0.002$. The diagram of (Yoon et al. 2006) also indicates that, for metallicities $Z \lesssim 0.002$, the WR phenomenon can appear in stars having lower masses than those in the Milky Way (hereafter MW). In this context, Martins et al. (2009) have observed several SMC WR stars, whose evolutionary status and chemical properties can be understood if they are fast rotators.

According to the listed observational and theoretically inferred requirements, stars might be potential LGRBs progenitors if they

- are massive enough at the end of their evolution to form a black hole;
- have lost their hydrogen envelope and have a fast-rotating core;
- are formed in low-metallicity environments, where there must also be high star-formation rates to ensure having enough massive stars.

Since the lower the metallicity the faster the rotation and the lower the mass of stars that can undergo the WR phase, according to Yoon et al. (2006), the most massive B-type stars, as well as O-type stars, could become WR stars if they rotated fast enough. The required rotational velocities must be close to those what are typical of Oe/Be stars. Then, we simply ask whether the more massive stars displaying the Be phenomenon today in the SMC, can be potential progenitors of LGRBs. This possibility has already been raised by Woosley & Heger (2006). We recall that the "Be phenomenon" appears in the main sequence evolutionary phase of fast-rotating O- and B-type stars. They are characterized by emission lines produced in a decretion disk formed by continuous and episodic matter ejections from the central star. These objects are the fastest known rotators in the main sequence, and their rotation can be closer to the critical one when the metallicity is lower (Domiciano de Souza et al. 2003; Meilland et al. 2007; Frémat et al. 2005; Vinicius et al. 2006; Martayan et al. 2007).

Our research on whether the SMC Oe/Be stars can be progenitors of LGRBs is based on three tests: 1) determination of the global specific stellar angular momentum (Sect. 2), 2) inference of the ZAMS angular velocity ratios of the studied SMC Oe/Be stars and comparison with the model predicted requirements to be LGRB-progenitor (Sect. 3), and 3) estimation of the LGRBs rate based on the SMC Oe/Be- and fast-rotator population, and its comparison with the observed ones (Sect. 4). A general discussion is given in Sect. 5.

2. Inference of the ZAMS rotational velocities

2.1. Main sequence linear equatorial rotational velocities

The results presented in this section are based on the FLAMES-GIRAFFE (Pasquini et al. 2002) observations discussed in Martayan et al. (2007)[1]. To the previous sample of 131 Oe/Be stars analyzed by Martayan et al. (2007), we added here the most massive Be stars and Oe stars found in the SMC. The projected rotational velocity $V \sin i$ of each star was determined with the GIRFIT code (Frémat et al. 2006). The average values of $V \sin i$ by mass category thus obtained are given in Table 1. We know, however, that Oe/Be stars are fast rotators, and the gravitational darkening effect (hereafter GD) induces systematic underestimations of the $V \sin i$ parameters (Townsend et al. 2004; Frémat et al. 2005). In this work we have corrected the measured $V \sin i$ quantities using similar curves to those given in Frémat et al. (2005) but recalculated for the SMC metallicity. The corrected average rotational parameters per mass category are presented in Table 1 as $\langle V \sin i \rangle_{\rm corr}$.

Figure 1 shows the $\langle V \sin i \rangle_{\rm corr}$ per mass category of the studied SMC Oe/Be stars, compared with three new theoretical tracks of true equatorial rotational velocities calculated by Ekström et al. (2008b) for metallicity $Z = 0.002$, which suits the SMC cluster NGC330 and its environment. In what follows, all models for SMC stars are for $Z = 0.002$. To compare the theory with observations, all model velocities were multiplied by $\pi/4 = \langle \sin i \rangle$ to simulate the

[1] Based on observations at the European Southern Observatory, Chile under project number 072.D-0245(A) and (C).

random distribution of the inclination i of the rotational axis (Chandrasekhar & Münch 1950). Once the fundamental parameters of all studied stars had been determined, the models of rotating stars were chosen so as to match the average true rotational velocity (i.e. $V = (4/\pi)V\sin i$) per mass category at their respective average age. The average true rotational velocities, V, per mass category have uncertainties ranging from 20 to some 40 km s^{-1}(cf. Table 1). The inferred average ZAMS velocities for these mass categories are then affected by uncertainties that are of the same order of magnitude, i.e. $\delta V \sim \pm 30$ km s^{-1}, on average (Martayan et al. 2007, their Fig. 9). For the near critical linear velocities, $V \sim V_{\rm c}$, and stellar masses $M \gtrsim 17M_{\odot}$, the corresponding $|\delta V/V_{\rm c}|$ translates into $|\delta(\Omega/\Omega_{\rm c})| \lesssim 0.05$ as the average uncertainty of the derived angle velocity ratios ($V_{\rm c}$ and $\Omega_{\rm c}$ are the linear and angular critical velocities, respectively).

The obtained today $\Omega/\Omega_{\rm c}$ ratios for all mass groups are in the interval $0.99 \lesssim \Omega/\Omega_{\rm c} \lesssim 1.0$. Fig. 1 shows the loci of today $\langle V\sin i\rangle$ against the mass corresponding to $\Omega/\Omega_{\rm c} = 0.99$ and 1.0. For comparison, this figure also includes the $\langle V\sin i\rangle$ curve for $\Omega/\Omega_{\rm c} = 0.90$.

A similar comparison in Martayan et al. (2007), made with observed rotational velocities that were not corrected for the underestimations induced by the GD effect, suggestes that the SMC Be stars rotate on average at $\Omega/\Omega_{\rm c}$=0.95. Within the observational uncertainties, the corrected velocities for the GD effect shown in Fig. 1 likely correspond to $\Omega/\Omega_{\rm c}$=0.99. We note that $\Omega/\Omega_{\rm c}$=0.99 is for a linear velocity ratio $V/V_{\rm c} = 0.97$ or for a ratio of surface centrifugal to gravitational accelerations $\eta = 0.90$.

Table 1. Values of the rotational velocities for Be and Oe stars for several average mass categories

Mass category $\langle M/M_{\odot}\rangle$	A 3.7	B 7.6	C 10.8	D 13.5	E 23.7
N	14	82	13	15	7
$\langle V\sin i\rangle$	277	297	335	336	420
$\langle V\sin i\rangle_{\rm corr}$	300	326	376	377	457
log[age(yr)]	8.3	7.6	7.3	7.2	6.9
$\langle V\rangle^{\rm old}_{\rm ZAMS}$	400	437	513	514	–
$\langle V\rangle^{\rm new}_{\rm ZAMS}$	448	487	562	563	683
$\epsilon_{V_{ZAMS}}$	35	27	23	23	44
$\langle V\rangle^{\rm magnet}_{\rm ZAMS}$	389	423	488	489	643

N = number of stars by mass category
$\langle V\rangle^{\rm old}_{\rm ZAMS}$ = average true rotational velocities in km/s without correction for GD (Martayan et al. 2007)
$\langle V\rangle^{\rm new}_{\rm ZAMS}$ = average true rotational velocities in km/s of the enlarged stellar sample, corrected for GD effect
$\epsilon_{V_{ZAMS}}$ = error of $\langle V\rangle^{\rm new}_{\rm ZAMS}$ in km/s
$\langle V\rangle^{\rm magnet}_{\rm ZAMS}$ = average true rotational velocities in km/s of the enlarged stellar sample,
corrected for models including magnetic fields

2.2. ZAMS rotational velocities

Using the same approach as in Martayan et al. (2007), which was based on models calculated by Maeder & Meynet (2001) and Meynet & Maeder (2002), we re-determined the ZAMS rotational velocities of the SMC Oe/Be stars with a new and more complete grid of curves representing the evolution of rotational velocities at low metallicity (Ekström et al. 2008b). The obtained results are given in Table 1. For the sake of comparison, this table also gives the previous average values of the ZAMS rotational velocities. The new results are shown in Fig. 2, where the theoretical ZAMS rotational velocities calculated by Ekström et al. (2008b) are also drawn for the SMC metallicity and for the angular velocity ratios $\Omega/\Omega_{\rm c}$ =0.90, $\Omega/\Omega_{\rm c}$ =0.99 and $\Omega/\Omega_{\rm c}$ =1.00. We notice then that SMC Oe/Be stars in the ZAMS rotate on average with $\Omega/\Omega_{\rm c}\simeq$0.95. The models do not include magnetic fields, thus the mean rotational velocity on the MS is lower than it would be for magnetic models. We might thus overestimate the initial ratio $\Omega/\Omega_{\rm c}$, which should be considered here as an upper limit. To take the difference in the models into account with magnetic fields, we compared the values of ZAMS velocities for given $\Omega/\Omega_{\rm c}$ values between the models from Ekström et al. (2008b) and from Yoon et al. (2006). The values of V$_{ZAMS}$ in the last row of Table 1 are then corrected by the corresponding scale factor.

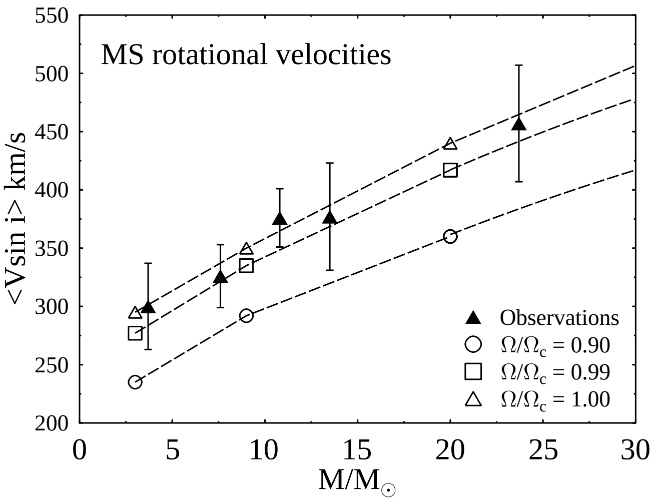

Fig. 1. Comparison of the average observed rotational velocities SMC of Oe/Be stars with the locus of theoretical velocities for the SMC metallicity. The curves are for model stars that attain the surface angular velocity ratios $\Omega/\Omega_{\rm c}$ =0.90, $\Omega/\Omega_{\rm c}$ =0.99 and $\Omega/\Omega_{\rm c}$ =1.00, in the MS evolutionary phase.

The trend of points inferred with the observation in Fig. 2 can be represented with $\langle V^{\rm obs}_{ZAMS}\rangle \simeq 301\times M^{0.26\pm0.05}$ km s^{-1}. For the inference of the specific angular momentum that must have the circumstellar disks hanging over the collapsed stellar cores, it is instructive to estimate the average specific angular momentum, $\langle J/M\rangle_{ZAMS}$, that the SMC Oe/Be stars have in the ZAMS. To this end, let us write $\langle J/M\rangle_{ZAMS} = k_{\rm G}\langle V^{\rm obs}_{ZAMS}\rangle\langle R_{ZAMS}\rangle$, where $k_{\rm G}$ is the gyration radius and R_{ZAMS} the stellar radius of stars in the ZAMS. The $k_{\rm G}$ and R_{ZAMS} radii

suited to $\Omega/\Omega_c = 0.95$, chosen according to what is suggested by the observed points in Fig. 2, varies with the mass as $k_G = 0.017 \times M^{0.13\pm0.02}$, while the radius varies as $\langle R_{ZAMS}\rangle = 1.72 \times M^{0.59\pm0.02}$, (Zorec 1986; Zorec et al. 1988; Ekström et al. 2008b). By taking the decrease in the stellar moment of inertia induced by a rigid rotation at $\Omega/\Omega_c = 0.95$ into account, we obtain the following expression for $\langle J/M\rangle_{ZAMS}$, valid for the whole mass interval $3 \lesssim M/M_\odot \lesssim 30$;

$$\langle J/M\rangle_{ZAMS} \simeq 6.0 \pm 0.1 \times 10^{16} (\frac{M}{M_\odot})^{0.98\pm0.08} \ \mathrm{cm^2 s^{-1}} \ , \quad (1)$$

which means that the average specific angular momentum of Oe/Be stars of the SMC in the ZAMS, considered as rigid rotators, increases linearly with the mass. Using moments of inertia calculated with stellar models at rest, Kawaler (1987) obtained for a mixed sample of B+Be stars in the MW that $\langle J/M\rangle \sim M^{1.43\pm0.16}$. Since the specific angular momentum of the last stable orbit around a Schwarzschild black hole scales with the mass $M/M_\odot$ as (Yoon et al. 2006) (3 times more than for a Kerr black hole)

$$(J/M)_{SBH} = 1.5 \times 10^{16} (\frac{M}{M_\odot}) \ \ \mathrm{cm^2 s^{-1}} \ , \quad (2)$$

the SMC Oe/Be stars would then have a specific angular momentum only a few times greater than the one that is supposedly appropriate for producing a stable disk over the black hole after the stellar collapse. Since part of this angular momentum will be lost during the evolutionary following the MS phase, the SMC Oe/Be stars do not seem to have angular momenta that is to prevent the formation of circumstellar disks and/or the expected jets (MacFadyen & Woosley 1999).

Because it may affect the properties of Oe/Be stars, after we take the average of the Ω/Ω_c rates over the masses in the ZAMS and in the MS, the equatorial velocity of these objects decreases from the ZAMS to the MS by a factor 0.76, while Ω/Ω_c varies from $\Omega/\Omega_c = 0.95$ to $\Omega/\Omega_c = 0.99$. This change in Ω/Ω_c implies that the ratio V/V_c varies from 0.87 to 0.97 and the ratio η of the surface equatorial centrifugal to gravitational acceleration passes from 0.76 to 0.90.

3. LGRBs progenitors and the Oe/Be stars

3.1. ZAMS rotational velocities of LGRBs progenitors compared to those of Oe/Be stars

Thanks to the combined effects mainly of rotation and metallicity, a series of models suggest that massive fast-rotating stars can fulfill the requirements imposed by the collapsar engine and be so progenitors of LGRBs (Hirschi et al. 2005; Yoon et al. 2006). To comply with the SN-LGRB relation, the involved stellar masses need to be higher than 10 M$_\odot$. Thus, while Hirschi et al. (2005) conclude, on the basis of non magnetic models, that for the SMC metallicity stars with masses between 32 and 92 M$_\odot$ are able to produce LGRBs, the latest models by Yoon et al. (2006), which include magnetic fields decrease the lower limit of masses to those of early B-type stars. According to these models, fast rotation favors a strong mixing of chemicals, which means that the stars can evolve as quasi-chemically homogeneous and finally end up as massive helium stars. Since the lower the metallicity, the faster the stellar rotation can be, these phenomenon can in principle be favored in media with low metallicity, which accordingly impede strong stellar winds. In turn, this makes the stars conserve high amounts of angular momentum. The models by Yoon et al. (2006) predict a lower limit to the ratio of equatorial linear velocities V/V_c (V_c is the critical or breakup velocity) as a function of mass for the LGRB progenitors that do not seem to change strongly according to the metallicity, but the limiting V/V_c ratio increases if the stellar mass is lower. Moreover, the zone above the threshold V/V_c ratio of potential LGRB progenitors widens towards lower and higher masses as the metallicity decreases.

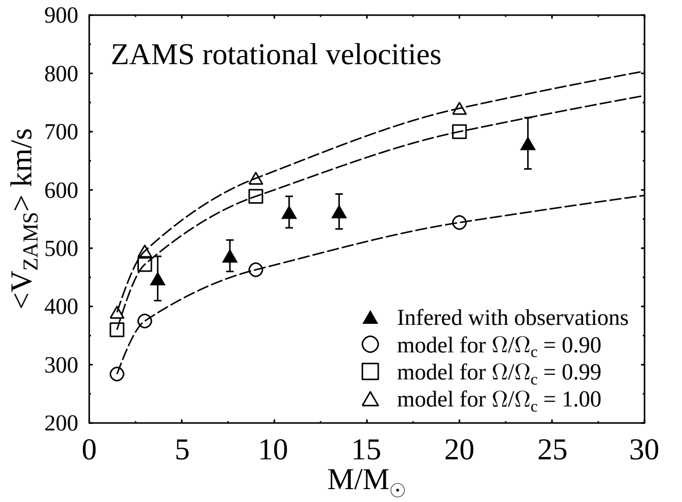

Fig. 2. Inferred ZAMS rotational velocities of SMC Oe/Be stars (triangles) compared with model SMC ZAMS rotational velocities from Ekström et al. (2008b) (dashed curves).

Campana et al. (2008, and references therein) indicate that the LGRB GRB060218 had a progenitor with an initial mass of 20 M$_\odot$, i.e., a B0-B1 star, where the metallicity is $Z = 0.004$, similar to the SMC. The chemical composition of the nebulae surrounding the star, if it is assumed that it reflects the chemical abundance of the progenitor, indicates that the progenitor was a near critical rotator, as in the "Be phenomenon". Such a fast rotation is required to produce an efficient mixing process in the star, which favors the stellar chemically homogeneous evolution and makes it possible for the environing nebulae reflect the stellar abundances.

To compare the models with the inferred ZAMS ratios Ω/Ω_c, we transformed the 'observed'[2] $(V/V_c)_{\rm ZAMS}$ ratios of the Oe/Be star subsamples in the SMC into Ω/Ω_c ratios by considering the 1σ dispersion of masses and equatorial velocities intervening in each average. The V/V_c and Ω/Ω_c ratios for massive stars are related as (Chauville et al. 2001)

$$\frac{\Omega}{\Omega_c} \simeq 1.381 \frac{V}{V_c} \big[1 - 0.276 (\frac{V}{V_c})^2\big] \ , \quad (3)$$

which is also valid for the SMC metallicity. These results are given in Table 2. The indicated mass category, i.e. A$\pm\sigma$M,

[2] Actually, $(V/V_c)_{\rm ZAMS}$ must be understood as values inferred from observed V/V_c ratios through model predicted tracks of the stellar rotational velocity.

should be understood as $M(\mathrm{A}) \pm \sigma\mathrm{M}$. The boldfaced value of the Ω/Ω_c in % corresponds to the average mass $\langle\mathrm{M}\rangle$ of the corresponding subsample. The natural upper limit of the surface stellar rotation is obviously given by $V/V_\mathrm{c} = 1.0$. In Table 2 all values $V/V_\mathrm{c} > 1.0$ are the arithmetic consequences of the imposed symmetric 1σ dispersions and they should be understood as $V/V_\mathrm{c} \rightarrow 1.0$. In Table 3, the values of Table 2 are corrected for the effect of magnetic fields from the Yoon et al. (2006) models as explained in Sect. 2.2.

Table 2. Ratios of the ZAMS Ω/Ω_c per mass category of SMC Oe/Be stars with the boldfaced values corresponding to the average Ω/Ω_c ratios of subsamples.

Mass category	Ω/Ω_c	$\Omega/\Omega_\mathrm{c}-\sigma$	$\Omega/\Omega_\mathrm{c}+\sigma$
A	**0.89**	0.79	1.01
A$-\sigma$M	0.94	0.83	1.04
A$+\sigma$M	0.85	0.75	0.96
B	**0.87**	0.68	1.08
B$-\sigma$M	0.93	0.73	1.15
B$+\sigma$M	0.82	0.64	1.01
C	**0.92**	0.71	1.08
C$-\sigma$M	0.94	0.72	1.09
C$+\sigma$M	0.91	0.70	1.06
D	**0.91**	0.63	1.07
D$-\sigma$M	0.95	0.66	1.13
D$+\sigma$M	0.87	0.60	1.02
E	**0.92**	0.78	1.02
E$-\sigma$M	1.03	0.88	1.15
E$+\sigma$M	0.82	0.70	0.91

The inferred ZAMS zones of Ω/Ω_c ratios per mass category of SMC Oe/Be stars given in Table 3 are compared in Fig. 3 with the theoretically predicted region containing the LGRB progenitors for $Z = 0.002$ by Yoon et al. (2006). One can see that only the more massive Oe/Be members, found in the "E-category", may reach the zone of potential LGRBs progenitors. According to Yoon et al. (2006), the ratio of the core to envelope mass is low in the less-massive O/B stars, which favors an efficient braking of their core and thus a significant reduction of its specific angular momentum. These stars were then not included in our counting as potential LGRBs progenitors. Nevertheless, among the less massive OB objects, there may be many that are possibly storing high amounts of angular momentum, thanks to strong internal differential rotation. In these objects, the core specific angular momentum can then be higher than the one predicted with stellar evolutionary models constructed with an initial upper limit of kinetic energy imposed by the rigid rotation in the ZAMS. Thus, in spite of the limiting masses imposed by the above mentioned theoretical predictions, many more stars could be potential LGRBs progenitors. The same arguments can also be extended to stars, of the same and other masses, which are here excluded from the counting because of their apparent low surface rotation. We discuss this issue in Sect. 5.

In Fig. 3 the shaded "E" zone seems to show somewhat an unusual behavior compared to other mass categories.

Table 3. Ratios of the ZAMS Ω/Ω_c per mass category of SMC Oe/Be stars corrected for the effect of magnetic field from the comparison between Ekström et al. (2008b) and Yoon et al. (2006) models (boldfaced values correspond to the average Ω/Ω_c ratios of subsamples).

Mass category	Ω/Ω_c	$\Omega/\Omega_\mathrm{c}-\sigma$	$\Omega/\Omega_\mathrm{c}+\sigma$
A	**0.77**	0.69	0.88
A$-\sigma$M	0.82	0.72	0.90
A$+\sigma$M	0.74	0.65	0.83
B	**0.76**	0.59	0.94
B$-\sigma$M	0.81	0.63	0.99
B$+\sigma$M	0.71	0.56	0.88
C	**0.80**	0.62	0.94
C$-\sigma$M	0.82	0.62	0.95
C$+\sigma$M	0.79	0.61	0.92
D	**0.79**	0.55	0.93
D$-\sigma$M	0.82	0.57	0.98
D$+\sigma$M	0.76	0.52	0.89
E	**0.83**	0.70	0.92
E$-\sigma$M	0.93	0.79	1.03
E$+\sigma$M	0.75	0.63	0.82

Although we are not able to specify which of them is dominant, four reasons may be used together to explain it: 1) the smallness of the stellar sample which by chance perhaps favors the highest $V\sin i$ values; 2) fast evolution of massive stars in low-metallicity regions that enables the initial high angular momentum to be retained; 3) the overestimated $V\sin i$ of massive Oe/Be stars because of some systematic non rotational line broadening effect, i.e. electron scattering, etc.(Ballereau et al. 1995; Zorec et al. 1992); 4) the stronger mass-loss in the more massive stars, so that their surface Ω/Ω_c ratio is less likely to increase during the MS lifespan, see for examples Meynet & Maeder (2000, Fig. 11) and Maeder & Meynet (2001, Fig. 4).

Hunter et al. (2008) indicated that, according to the $V\sin i$ distributions of B stars they observed in NGC 346, the areas of LGRBs progenitors could be more extended than expected from Yoon et al. (2006) model predictions. The age of this cluster is roughly 3-5 Myrs (Nota et al. 2006; Bouret et al. 2003), there have been recent episodes of star formation and it hosted at least 1 supernova (Gouliermis et al. 2008). In this region there are also several classical Be stars and other emission-line objects (Wisniewski & Bjorkman 2006; Wisniewski et al. 2007; Hunter et al. 2008; Martayan et al. 2010).

3.2. Evolution of Oe/Be and WR stars

Some stars could start in the ZAMS as born Oe/Be objects, but lose this property during their MS life-span due to the spin-down produced by efficient mass-/angular momentum-loss phenomena. This can be the case of the massive Be stars in the MW, which are only found in the first half of the MS (Zorec et al. 2005). Contrary to the MW, the massive Oe/Be stars and Oe stars in the SMC are also present in the second half of the MS. These stars can then continue their post-MS steps by keeping fast rotational rates and

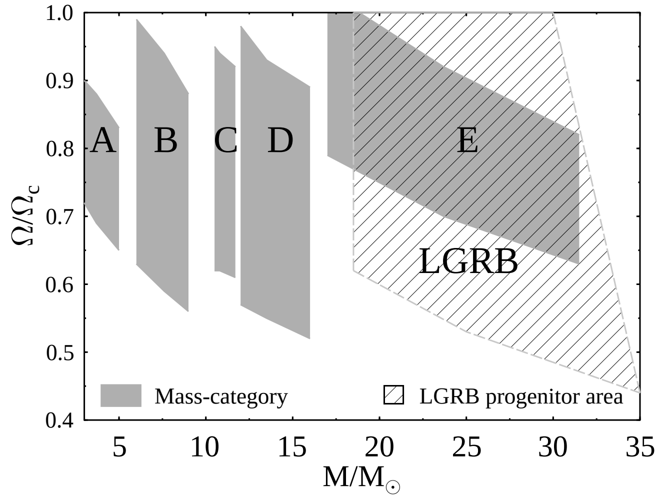

Fig. 3. Comparison of the (Ω/Ω_c, $M/M_\odot$) parameters in the ZAMS per mass category for SMC Oe/Be stars with the area of long gamma ray bursts progenitors at SMC metallicity predicted by Yoon et al. (2006).

evolve as chemically quasi-homogeneous objects towards the fast-rotating WR phase (Yoon et al. 2006). This prediction seems to be supported by Martins et al. (2009), who find that several SMC WR stars are certainly fast rotating objects.

The finding in Sect. 3.1 that the more massive members of the SMC Oe/Be population overlaps the LGRBs predicted progenitor area (Yoon et al. 2006), thanks to their masses and $(\Omega/\Omega_c)_{\rm ZAMS}$ rotation rates, which are today in the second half of their MS evolutionary phase, makes them designed candidates for such chemically quasi-homogeneous objects that can evolve towards the WR phase and become LGRB progenitors later on.

Martayan et al. (2010) find that the "Be phenomenon" can be shared by more numerous stellar populations, favored possibly by the lower SMC metallicity, than in the MW. Since the theoretical predictions show that the lower the metallicity the lower is the stellar mass that can enter the LGRB progenitor area, it is expected that among the massive stars of the first generations, which are very metal poor, there might be a significantly large number of objects that could have undergone the "Be phenomenon". These stars could then have had the required physical conditions for being potential LGRB progenitors.

4. Predicted LGRBs rates from the Oe/Be star population and comparison with the observed ones

Another test of the ability of the Oe/Be stars in the SMC to be LGRBs progenitors is based on the estimation of the expected rate of LGRB events that these stars can afford. In the less favorable case, the predicted frequency must be of the same order of magnitude as the observed ones for this stellar population be considered a plausible candidate.

4.1. The SMC Oe/Be stellar population and selection of candidates

To estimate the LGRB rate from the SMC Oe/Be stellar population, we need to identify the right spectral types to fill the mass requirements of stars entering the theoretically predicted LGRB progenitor zone shown in Fig. 3. To this end, and knowing that we are dealing with fast rotators, we used the models of stellar evolution with rotation for stars with SMC metallicity calculated by Maeder & Meynet (2001). We interpolated the evolution paths from the ZAMS to the TAMS for the masses $M = 18M_\odot$ and $M = 33M_\odot$. The $(\log L/L_\odot, T_{\rm eff})$ corners thus obtained in the theoretical HR diagram were transformed into absolute magnitude-color pairs $[M_{\rm V}, (V-I)_o]$ using standard bolometric corrections and the OGLE-III color-magnitude calibrations in current use. It follows from this that the main sequence visual absolute magnitudes of SMC stars with $M = 18M_\odot$ range from $M_{\rm V} = -2.8$ mag to $M_{\rm V} = -4.4$, while those of $33M_\odot$ do it from $M_{\rm V} = -3.7$ mag to $M_{\rm V} = -6.3$. A mass-spectral type correspondence for stars in the ZAMS has also been recently obtained by Huang & Gies (2006).

In accordance with the MK spectral-types for dwarf stars in the SMC calibration against the visual absolute magnitude $M_{\rm V}$ used in (Martayan et al. 2010), the stars entering the LGRB progenitor zone in Fig. 3 correspond then to those labeled with B1-O8 spectral types for rest and emission-less stars. However, according to Hunter et al. (2008) the mass of the LGRBs progenitors could be as low as $14M_\odot$. In this case, one should count stars a little cooler than spectral type B1, i.e. from B1.5, up to O8 as potential LGRBs progenitors with SMC metallicity. Stars from 14 to 33 $M_\odot$ evolve in the MS phase, so that their respective absolute magnitudes $M_{\rm V}$ remain rather constant and that the $(V-I)_0$ color changes by no more than $\delta(V-I)_0 \sim 0.04$ mag for 14 $M_\odot$ to $\delta(V-I)_0 \sim 0.07$ mag for 33 $M_\odot$. Moreover, in our $[M_{\rm V}, (V-I)_0]$ diagram, all counted OB stars are located in quite a narrow strip of $M_{\rm V}$ as a function of $(V-I)_0$ (see Fig. 5 in Martayan et al. 2010), so that there cannot be much confusion regarding the identification of stars by their masses with the employed photometric criterion.

The absolute magnitude intervals for 18 and $33M_\odot$ stars were established from evolutionary models where the $(\log L/L_\odot, T_{\rm eff})$ parameters are averaged over the rotationally deformed stellar surfaces. Actual stars show, however apparent hemisphere-dependent spectroscopic and photometric characteristics. There are then at least two reasons, rotation- and Be phenomenon-related, for which still cooler spectral types than B1 should enter the counting: 1) fast-rotating stars appear with cooler apparent spectral types than stars with the same mass at rest (Frémat et al. 2005; Martayan et al. 2007); 2) the largest number of candidate stars are selected using photometric colors in the visible and near-IR, where both rotation and the presence of circumstellar disks make the stars appear strongly reddened. We recall that reddening due to the circumstellar disks $\Delta(B-V) \gtrsim 0.05$ mag are currently observed in Oe/Be stars (Moujtahid et al. 1998, 1999; Martayan et al. 2010). These two effects make that the stars with photometrically determined spectral types can appear from two to three subspectral types cooler than expected for their intrinsic rest spectrum, so that in principle the counting could start at spectral type B3.

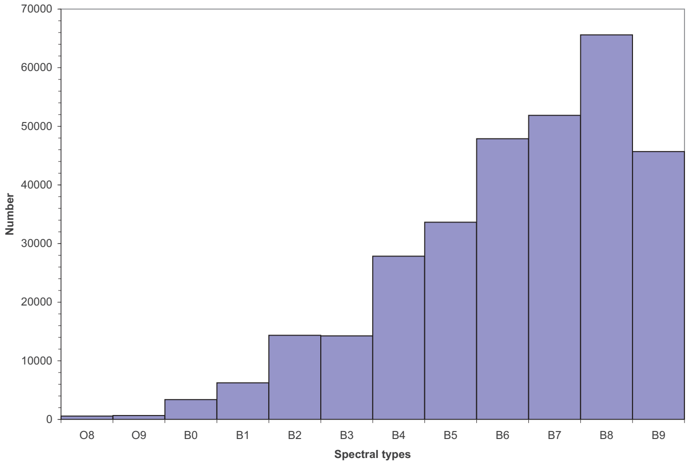

Fig. 4. Spectral-types distribution of OB stars in the SMC counted with OGLE-III.

As a consequence of the many effects determining the apparent spectral type of Oe/Be stars, the mass-spectral type mismatch can be high. Since the number of stars increases rapidly as the spectral type becomes cooler, we prefer to deal with a lower limit of counted candidates. We thus considered stars only from the apparent spectral type B2 and hotter. Once the number of all O/B stars, i.e. with and without emission lines, that enter the chosen range of spectral types in the SMC, we determine the number of Oe/Be stars using the frequencies of Be and Oe stars given by Martayan et al. (2010), which are based on a slitless survey of emission-line stars in the SMC.

The counts of all O/B stars entering the desired spectral type ranges were performed using the new OGLE-III catalog (Udalski et al. 2008), which covers 14 square degrees, so that both the bar and the external fields of the SMC are covered. We note that OGLE-II data cover only 2.4 square degrees. Its use would require extrapolating the number of OB stars for regions off the bar to infer the total number of O/B stars in the SMC with the required spectral types.

The stars were selected using the dereddened color diagram $[M_{\rm V}, (V-I)_o]$. To do the correction for the ISM extinction, we calculated the mean E[B-V] color excess based on the individual values from the SMC clusters (see Pietrzynski & Udalski 1999), which amounts to 0.084 mag and is similar to the E[B-V]=0.08 mag given by Keller et al. (1999). Then the absolute $M_{\rm V}$ and the dereddened $(V-I)_o$ were obtained following the same process as described in Martayan et al. (2010). Using the calibrations by Lang (1992) and Sagar & Cannon (1997), the E[V-I] is obtained by the formula:

$$E[V-I] = 1.44 \times E[B-V] + 0.0175 \times E[B-V]^2 \ , \qquad (4)$$

where the second term is negligible with E[B-V]=0.084. And finally the $(\mathrm{V-I})_0$

$$(V-I)_0 = (V-I) - 1.44 \times E[B-V] \qquad (5)$$

The number of OB stars in the SMC with and without emission lines so determined per subspectral type from B3 to O8 is shown in Fig. 4, and detailed in Table 4 for types between B3 and O8. The distribution in Fig. 4 shows that O and B-type stars basically follow the IMF except that the OGLE-III survey is not complete towards the late B stars, which explains the sudden decrease in counts at B9. We are finally left with the following reference number of objects to predict the rate of LGBRs events:

Table 4. Counts of OB main sequence stars with and without emission in the SMC per spectral type with OGLE-III.

O8	O9	B0	B1	B2	B3
566	671	3482	6269	14406	14332

$$\begin{aligned} N_{\rm tot} &= \ \ 4719 \text{ stars hotter than B0} \\ N_{\rm tot} &= 10988 \text{ stars hotter than B1} \\ N_{\rm tot} &= 25395 \text{ stars hotter than B2} \\ N_{\rm tot} &= 39726 \text{ stars hotter than B3.} \end{aligned} \qquad (6)$$

Since the FWHM of the OGLE-III PSF function is better than 1.34″, it implies that in the SMC the counted early-type stars must be separated by at least 0.33 pc for their images not to merge. According to a recent study by Sabbi et al. (2009), the highest early-type star density in the SMC is 8.5 star/pc^2, which implies mean stellar separations of 0.34 pc. This ensures that the counting in Table 4 is complete.

In the next section we estimate the rates of LGRBs events and the number of LGRBs in the local universe. Their purpose is to get the range of uncertainties that can affect the estimate of rates depending on those inherent to stellar counts and the angles of beams.

4.2. Prediction of the LGRB rates

To predict the number of LGRBs seen from Earth, we consider only specific beaming angles. In a first step, we determine the number of Oe/Be stars per spectral-type. We use for that the Be/(B+Be) and Oe/(O+Oe) ratios in the SMC determined by Martayan et al. (2010). The numbers of stars being sought are given in column 2 of Table 5, where the ranges stand for the uncertainties on the Be/B fractions. The yearly frequency of LGRB events is then obtained by dividing the counts per mass category by the respective total lifetime. The stellar ages used were interpolated among those obtained for this purpose by Yoon et al. (2006) for stars between 13 and 30M$_\odot$ with SMC metallicity. Assuming that the LGRBs only refer to single fast-rotating stars, we remove the binaries from the counts. As from Porter & Rivinius (2003) the binary rate is about 30% among Oe/Be stars, the obtained above rates must be multiplied by 0.7; however, the exact ratio of binaries in B-type stars is far from being well known. Among the hottest ones and in particular for O stars, the frequency of binary systems can reach 75% (Sana et al. 2008, 2009). It is worth noting that only those binaries should be removed where the interaction between the components is significant, which is not always the case in Be-binary systems. Finally, we stress that the Martayan et al. (2010) survey is a single-epoch survey. Because of the variable character of the Be phenomenon, according to Fabregat (2003) and McSwain et al. (2008) one third of the Be stars can be missing. As a consequence, the final range of rates of LGRBs is calculated by multiplying the above rates by 0.7/(1-1/3).

The LGRBs rates obtained for the SMC are called here the “LGRB base-rates”. They represent the intrinsic rates

that we generalize to all irregular galaxies of Magellanic type, which are metal poor and can host LGRBs progenitors. The LGRB base-rates are thus given by

$$R^{\rm br}_{\rm LGRB} = \left(\frac{0.7}{1-1/3}\right) \times \sum_{Sp} \left[\frac{N_{\rm Oe/Be}(Sp)}{t(Sp)}\right] \quad \text{LGRBs/yr} \qquad (7)$$

In this relation, $N_{\rm Oe/Be}$(Sp) is the number of stars with spectral type Sp displaying the Be phenomenon, and $t(Sp)$ is the total lifetime of stars with spectral type Sp in the early MS evolutionary phases. The constant factor in relation (7) is of the order 1, which indicates a fortuitous compensation between the fraction of rejected stars for binarity and the completeness factor for missing Oe/Be stars. The $R^{\rm br}_{\rm LGRB}$ rates calculated with (7) are given in column 3 of Table 5.

Since the LGRB phenomenon is strongly collimated, to obtain the potential rates that can be observed, in a second step we have to multiply the base-rates by the the probability that beaming angle sweep the Earth. The beam angles θ can range from 0.5^o to 15^o (Hirschi et al. 2005; Fryer et al. 2007; Lamb et al. 2005; Watson et al. 2006; Zeh et al. 2006). The probability that a beam of angle θ be seen at Earth is:

$$p(\theta) = \int_0^\theta \sin\theta \ {\rm d}\theta \ , \qquad (8)$$

Finally, to calculate the predicted yearly rate of LGRB events per average galaxy in a given volume of the Universe, we have to take the fraction of galaxies into account that have the required properties in this space to host LGRB progenitors. Let us then assume that the SMC properties regarding the frequency of fast rotators with low metallicity is partaken by the irregular Magellanic-type galaxies (Im-type), which are metal poor. We note this fraction as $f_{\rm Im} = N_{\rm Im}/N_{\rm G}$, where $N_{\rm Im}$ is the number of Im-type galaxies in a given volume of the Universe, and $N_{\rm G}$ the number of all galaxies in the same volume of space. According to statistics by Rocca-Volmerange et al. (2007), it is $f_{\rm Im} = 0.17$, which is a very lower limit and valid up to at least redshift $z \sim 0.5$.

We present the results for the angles $\theta =: 5°$, $10°$, and $15°$, which are used by Podsiadlowski et al. (2004). However, the angle $\theta =: 5°$ according to Watson et al. (2006) is quite frequent. The angle 10^o is roughly in the middle of the observed interval of opening angles and the angle 15^o was chosen because is nearly the most opened one, although the least probable, but quite frequently evoked and used in the literature. It then happens that $p\!=\!0.0038$ for an angle of 5°, $p\!=\!0.015$ for 10°, and $p\!=\!0.0341$ for 15°. As there are 2 cones in each LGRB event, the probability (8) has to be multiplied by a factor 2. Thus, the predicted yearly rates of LGRB events per average galaxy produced in the local Universe, $R^{\rm pred}_{\rm LGRB}$, given in columns 4 to 6 of Table 5 were obtained from

$$R^{\rm pred}_{\rm LGRB}(\theta) = R^{\rm br}_{\rm LGRB} \times 2p(\theta) \times f_{\rm Im}. \qquad (9)$$

The observed yearly rate of LGRB events per average galaxy that we use as a reference in this work to which we compare the predicted ones from OeBe stars is obtained from the total rate of GRBs, of which 2/3 are considered of long-duration. From the BATSE monitoring it is found that $R^{\rm obs}_{\rm LGRB} \sim (0.2-3)\times 10^{-7}$ LGRBs/year/galaxy, where the extreme values concern the local Universe or the whole Hubble volume, respectively (Zhang & Mészáros 2004; Podsiadlowski et al. 2004; Fryer et al. 2007). According to the $(\Omega/\Omega_{\rm c}; M/M_\odot)$-area of LGRBs progenitors indicated by Yoon et al. (2006) and the mass-calibration by Huang & Gies (2006) or Lang (1992), but neglecting spectral type changes from rotational and circumstellar effects discussed in Sect. 4, we should only consider counts of stars hotter than spectral types B0-B1. Taking the beaming angles from 5^o to 15^o into account, we note that the estimates made with populations of Be/Oe stars from B0e to O8e overlap the observed range of LGRBs rates adopted above. The hottest populations (O9e to O8e) alone are not able to reproduce the rates.

Another way of comparing the predicted rates with the observed ones is to determine the number of LGRBs observed in the local Universe up to a given redshift z. The number of LGRB events that have taken place in the local Universe and have been seen from Earth during the last Y years, is given by:

$$N^{\rm pred}_{\rm LGRB} = R^{\rm pred}_{\rm LGRB}(\theta) \times N_{\rm G} \times Y, \qquad (10)$$

where $N_{\rm G}$ is the number of galaxies of all type counted up to a redshift z. We chose $z = 0.2$, since the number of galaxies in this volume seems to be about well determined. From the 2MASS catalog (Skrutskie et al. 2006)[3], we obtain $N_{\rm G}(z \le 0.2) = 1\,140\,931$ galaxies. Adopting $Y = 11$ years (see below), the predicted number of LGRB events seen from Earth are given in Table 6.

Using the GRBox from the University of California at Berkeley[4] for years between 1998 and 2008, there are 8 LGRBs (080108, 060614, 060505, 060218, 051109B, 031203, 030329A, 980425) and 3 SGRBs (061201, 050709, 000607) with a redshift lower than 0.2. This proportion of 73% of LGRB and 27% of SGRB agrees with the proportion of 75-25% as reported by Zhang & Mészáros (2004) for the LGRBs-SGRBs.

Zeh et al. (2006) and Watson et al. (2006) have studied the distribution of opening angles, which is reproduced in Fig. 5. If the LGRB event rate was estimated considering this distribution of beam angles, the $2p(\theta)$ probability factor in relation (9) had to be replaced by the integrated probability P given by

$$P = 2 \times \int_{0^o}^{16^o} p(\theta)Q(\theta){\rm d}\theta = 0.015 \ , \qquad (11)$$

where $p(\theta) = 1 - \cos\theta$ is given by (8), and $Q(\theta)$ is the distribution shown in Fig. 5. From (11) we deduce that P defines an average opening angle of 7^o, roughly. We can then interpolate the corresponding LGRB rate or number of events in Tables 5 and 6, respectively, which gives $N^{\rm pred}_{\rm LGRB} \sim (2-5)\times 10^{-7}$ LGRBs/yr/galaxy or $N^{\rm pred}_{\rm LGRB} \sim 3-6$ LGRB events in the past 11 years. On account of the uncertainties that may affect not only our knowledge of the opening angle of beams or their distribution, but also the estimated rates of observed LGRB events in the local and Hubble Universe, we may consider that the counts limited to the spectral

[3] see also http://www.haydenplanetarium.org/universe/duguide/exgg_twomass.php

[4] see http://lyra.berkeley.edu/grbox/grbox.php?starttime=670702&endtime=091231

Table 5. LGRBs rates estimated with the first approach.

Mass category	Number of Be/Oe stars	LGRBs base rates	Proba 5°	Proba 10°	Proba 15°
B2e to O8e	4978-6110	3.9-4.8 $\times 10^{-4}$	2.5-3.1 $\times 10^{-7}$	1.0-1.2 $\times 10^{-7}$	2.3-2.8 $\times 10^{-6}$
B1e to O8e	2774-3244	2.6-3.0 $\times 10^{-4}$	1.7-1.9 $\times 10^{-7}$	6.7-7.7 $\times 10^{-7}$	1.5-1.7 $\times 10^{-6}$
B0e to O8e	1483-1551	1.7-1.8 $\times 10^{-4}$	1.1-1.2 $\times 10^{-7}$	4.4-4.6 $\times 10^{-7}$	0.98-1.0 $\times 10^{-6}$
O9e to O8e	257-294	5.3-6.2 $\times 10^{-5}$	3.4-4.0 $\times 10^{-8}$	1.4-1.6 $\times 10^{-7}$	3.1-3.6 $\times 10^{-7}$
O8e	118-135	2.4-2.8 $\times 10^{-5}$	1.6-1.8 $\times 10^{-8}$	6.2-7.2 $\times 10^{-8}$	1.4-1.6 $\times 10^{-7}$

Table 6. Number of LGRBs predicted in the local universe (z≤0.2) in 11 years.

Mass category	Number for angle=5°	Number for angle=10°	Number for angle=15°
B2e to O8e	3-4	11-14	25-31
B1e to O8e	2-2	7-9	16-19
B0e to O8e	1-1	5-5	11-11
O9e to O8e	0-0	2-2	3-4
O8e	0-0	1-1	2-2

type interval B0-B1 to O8 predict rates that overlap rather well with the observed ones. This is the first time that an estimate of the LGRBs rates is done on the basis of a well-defined population of stars, i.e., born fast rotators with low initial metallicity.

Very recently, Georgy et al. (2009) has tried to reproduce the observed rates of LGRBs with models of WR stars. Although they obtained higher values of LGRBs rates than what observations seem to indicate, these authors conclude that only a fraction of WC/WO stars among those that initially were rapid rotators could produce gamma ray events. This fast-rotation argument may then focus some interest on stars with the characteristics discussed in the present work.

The counts of Oe/Be candidates for LGRB progenitors, as they were done here, however, represents a mere lower limit. Stars with masses corresponding to rest B0-B1 spectral types that rotate at $\Omega/\Omega_c \gtrsim 0.7$ following the requirements shown in Fig. 3 then display apparent spectral types cooler by at least one subspectral type. A prudent lower limit set at spectral type B2, would nevertheless enhance our predictions by a rough factor 2, as seen from counts displayed in (6), or Tables 5 and 6. However, massive fast rotators without emission lines should also be considered potential LGRBs progenitors as we see in Sect. 5.2, so that the final predicted rates may widely surpass the observed ones.

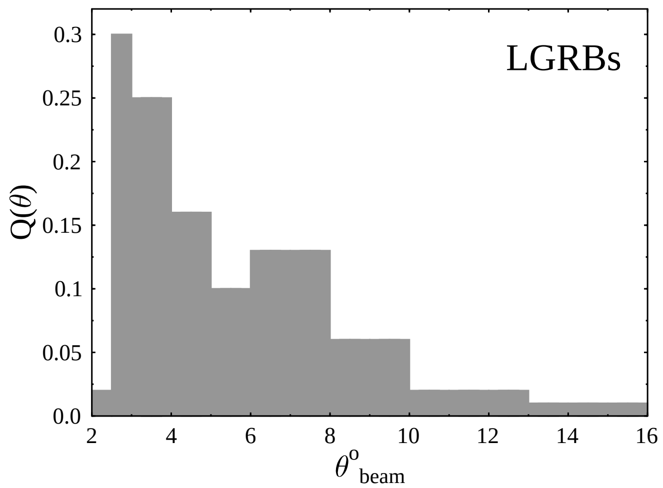

Fig. 5. Frequency of beam angles presented by Watson et al. (2006) and Zeh et al. (2006).

5. Other phenomena and possible biases in the LGRBs rate determination

5.1. Binaries

If the LGRBs could also occur in a binary system (Cantiello et al. 2007; van den Heuvel & Yoon 2007) under the same conditions as fast rotation and chemical composition, the rates we estimated above should be multiplied by 1/0.7. However, the results from Langer & Norman (2006) suggest that the binary evolutionary path is unlikely to produce LGRBs when they are associated with metal-poor galaxies (Kewley et al. 2007).

5.2. Fast rotators without emission lines

The ZAMS rotational velocities of Oe/Be stars in the MW form the tail of a true rotational velocity distribution $\Phi(V)$ that starts at a velocity limit given by $V_L = 30 \times (M/M_\odot)$ (Zorec et al. 2007). The tail of the velocity distribution formed by the Oe/Be stars can be represented with a Gaussian function, whose dispersion is also mass-dependent and is roughly given by $\sigma_V = 28 \times (M/M_\odot)$ (Zorec et al. 2007). This implies that there are rotators that can only acquire the Be phenomenon at the very end of their MS evolutionary phase, which cannot be seen as Oe/Be stars today. On the other hand, there are also fast rotating stars in the ZAMS that have slightly lower rotational velocities than V_L required to become Oe/Be, which will never display emission lines. However, it can easily be shown that they have a global specific angular momentum that is equal to or larger than given by Eq. 2, so that they certainly have enough angular momentum to be considered as candidates for LGRBs progenitors.

Let us also take into account those objects which in principle have the required angular momentum but were not included in our counting to derive the LGRBs rate. To this end we assume that they are rigid rotators. The equatorial velocity of all those having the specific angular momentum given by Eq. 2 is readily calculated to give $V_{\rm J} = 100 \times (M/M_{\odot})^{0.28}$. The fraction of objects yet not included in the estimated LGRB rates is then represented by the correcting factor q calculated as

$$q = \frac{1-\mathrm{erf}(x_{\rm L})}{1-\mathrm{erf}(x_{\rm SBH})}\ , \qquad (12)$$

for which, as noted above, we have taken the high velocity tail $\Phi(V)$ given by a Gaussian function. In Eq. 12 $\mathrm{erf}(x)$ is the error function, $x_{\rm L} = V_{\rm L}/\sqrt{2}\sigma_{\rm V}$, and $x_{\rm SBH} = V_{\rm J}/\sqrt{2}\sigma_{\rm V}$. The factor q then ranges from 1.2 to 1.5 for masses from 17 to $30M_{\odot}$. We can then multiply the LGRB rates found in Sect. 4 by an average factor $\overline{q} \simeq 1.35$, which increases even more the predicted rate well above the observed one and makes the massive fast-rotating stars highly probable progenitors of LGRBs.

Finally, from the equatorial velocity $V_{\rm J}$ required to attain the stellar specific angular momentum of the order given by Eq. 2, we derive the angular velocity ratios that range from $\Omega/\Omega_{\rm c} = 0.50$ to 0.52 for stars in the E-category in the ZAMS. This means that the LGRBs progenitor area: E mass-category of Fig. 3, can be entirely covered by the O/B-type fast rotators. Assuming that the distribution of the rotational velocities of the stars entering the LGRBs progenitor region in Fig. 3 foreseen by Yoon et al. (2006) is the same as used to calculated the fraction q in relation (12), it follows that our E mass group represents 44% of the stellar population in the LGRBs region.

5.3. Differential rotators

Models of stars that start in the ZAMS as rigid rotators, transform their original internal uniform angular velocity into a profile of differential rotation, where the stellar core rotates faster than the envelope Meynet & Maeder (2000), in no more than 2-3% of their MS lifespan. The latest theoretical works of stellar evolution with rotation claim, however, that magnetic fields through the Tayler-Spruit instability (Spruit 1999, 2002; Maeder & Meynet 2005; Yoon et al. 2006) are able to maintain the rigid rotation. Nevertheless, a recent critical discussion of the efficiency of the Tayler-Spruit instability by Zahn et al. (2007) shows that the action of magnetic fields can be much less efficient than previously thought. In all works of stellar structure, it is also assumed that convection imposes $\Omega =$ constant.

A number of discussions show that convection likely redistributes the specific angular momentum $j = \Omega r^2$ rather than Ω, which implies that in the convection zones the angular velocity should be $\Omega \propto r^{-p}$, where p is a positive quantity (Tayler 1973; Deupree 1998). In the Sun, the differential rotation exists precisely in the convective zones! Since the stars do not start their life in the ZAMS, but have passed though a long story before this phase, their internal rotation could already be differential in the ZAMS and with a larger content of angular momentum than just the allowed by a profile of rigid rotation. For an average star of $20M_{\odot}$, it is then a simple matter to calculate what must be in order of magnitude its ZAMS ratio of energies $\tau = K/|W|$, higher than some maximum $\tau_{\rm crit,rigid} = 0.015$ allowed by the rigid rotation (K is the rotational kinetic energy; W is the gravitational potential energy) in order for the star to keep up the same appearance as a rigid rotator throughout its MS evolutionary span. For that, we simply ask that the star fulfill at least two requirements: a) at any Lagrangian mass-coordinate the star never reaches the fateful limit $\tau \simeq 0.14$, which can make it secularly unstable and would tend to transform the delimited stellar volume into a three-axial Jacobian ellipsoid; b) during the whole MS phase it has on the surface $V_{\rm equator} \lesssim V_{\rm critical}$. Calculations show that these conditions can be fulfilled by $\tau_{\rm ZAMS} \simeq 0.03$, which is roughly two times $\tau_{\rm crit,rigid}$ in the ZAMS.

If by chance O/B stars started their MS life span as neat differential rotators with $\tau > \tau_{\rm crit,rigid}$, the internal mixing processes can be strong in a large number of stars where this phenomenon is unexpected a priori because of their apparently slow rotation. Then make their chemical composition attain the required properties to become potential LGRBs progenitors. Consequently, the estimate of the SMC $R_{\rm LGRB}$ rate we made in this paper might still be increased with stars of a wider variety of masses and apparent low surface velocities.

5.4. Underluminous GRBs

Recently, it has been discovered that underluminous GRBs (Fryer et al. 2007; Foley et al. 2008) could not be observed by the gamma ray satellites or not be classified as a GRB. According to these authors, this finding indicates that there may be a population of events that are less luminous but are possibly from 10 to 10^2 times more frequent. If these events are also considered, the local rate of GRBs could then amount to $\sim 10^{-6} - 10^{-5}$ LGRBs/year/galaxy. If correct, this last rate will indicate that other masses or kinds of stars can also be concerned such as less-massive B stars, in particular Bn stars. these stars are objects with spectral types that are most frequently later than B7. Moreover, they are fast rotators that do not have emission lines.

5.5. Other possible progenitors

According to Hammer et al. (2006), runaway WR stars could be another potential progenitor, but it is very difficult to estimate their impact on the LGRBs rates.

5.6. The "first stars" and the LGRBs

Using the GRBox from 1998 to 2009, we computed the statistics of GRBs by type with intermediate (z≥3) and high redshifts (z≥5). In the intermediate-z category, most of the GRBs are found to be long-GRBs (29 LGRBs, 2 SGRBs, 8 unknown). In the high-z category, the result is similar, 6 are LGRBs or type II, 2 are unknown, and 0 are SGRBs. The very high redshift GRB080913 was reclassified as a type II GRB by Zhang et al. (2009). And the most distant object known, GRB 090423, which has a redshift of 8.2, is also an LGRB or type II GRB (Salvaterra et al. 2009; Tanvir et al. 2009; Zhang et al. 2009). According to Salvaterra et al. (2009), the properties of the very-high redshift LGRBs are similar to those of low/intermediate red-

shift. According to Yoon et al. (2006) models, the number of LGRBs should increase with the redshift and the decrease in Z until the first stars. However, the number of LGRBs, which can originate in Pop III stars, is limited by this type of population. At high redshift it is expected that the stars have very low metallicity and are similar to the first stars. In this case, they can reach rotational velocities as high as 800 km s^{-1}, or even higher, as shown by Chiappini et al. (2006) and Ekström et al. (2008a). Ekström et al. (2008a) and Meynet & Maeder (2007) show that these stars can also retain enough angular momentum in their core to collapse into black holes and produce an LGRB. Moreover, Hirschi (2007) show that the stars with extremely low metallicity can rotate very fast and produce LGRBs. All these theoretical results agree with the statistics reported above and indicate that the stellar rotation close to the breakup velocity, as in the Be-phenomenon at low metallicity, is a key ingredient for the production of LGRBs. As a consequence, the LGRBs at high redshift should find their origin in the fast-rotating first stars.

6. Conclusion

While the first models focused primarily on fast-rotating WR stars as probable progenitors LGRBs, the latest developments indicate that fast-rotating, low-metallicity massive B- and O-type stars could also be behind the LGRBs. Such massive B- and O-type stars can actually be the Be and Oe stars of low metallicity found in the SMC. To test this assumption, we used fundamental parameters derived for Oe/Be stars in the SMC observed with VLT-FLAMES instruments. We first compared the average $V\sin i$ determined for several mass subsamples of SMC Oe/Be stars with the theoretically predicted rotational velocities. We found that today these objects on average have a surface angular velocity ratio $\Omega/\Omega_c \simeq 0.99$. Then, we determined the ZAMS rotational velocities again for Be stars in the SMC that we had studied in previous works and determined the ZAMS rotational velocities for a new subsample composed by SMC Oe stars. The average angular velocity rate of all these objects in the ZAMS is $\langle\Omega/\Omega_c\rangle = 0.95$. The ZAMS Ω/Ω_c rates thus determined were compared with those of fast-rotating massive stars foreseen by model calculations of LGRBs progenitors having an initial metallicity similar to the average one in the SMC. This comparison indicates that massive Oe/Be stars in the SMC could certainly have the properties required to be taken as LGRBs progenitors. A lower limit of 17% of galaxies in the near Universe are of irregular Magellanic-type that, by definition, all have metallicities $Z \lesssim 0.002 - 0.004$. All can then host LGRBs progenitors. From the discussion it appears that not only can massive Oe/Be stars be LGRBs progenitors, but a larger population of O/B stars without emission, which are less massive and with apparent lower surface rotation velocities, can also partake of this quality. The total number of LGRBs estimated from the Oe/Be star populations based on spotted beaming angles and counts from B0-B1 to O8 stars is on average $R^{\rm pred}_{\rm LGRB} \sim 10^{-7}$ to $\sim 10^{-6}$ LGRBs/yr/galaxy, which represent $N^{\rm pred}_{\rm LGRB} \sim 2$ to 14 in 11 years. These predictions increase beyond the observed ones, if the stellar counting starts at spectral types B1-B2, in accordance with the apparent spectral types of massive fast rotators. Massive fast rotators without emission lines can still enhance these predictions by more than 30%. On account of all possible uncertainties that may affect the calculated and the observed rates of LGRBs in the local Universe, we can consider that both overlap correctly. Young star formation regions in the SMC like NGC346 could then have hosted or will host one LGRB in the next Myrs.

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